

Improving Attachments of Non-Invasive (Type III) Electronic Data Loggers to Cetaceans

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Award Number: N00014-11-1-0113
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LONG-TERM GOALS

The overall goal of this project is to increase the longevity of suction cup attachments for short term archival tags such as the DTAG.

OBJECTIVES

We are working to extend the routine attachment duration for suction-cup tags to multiple days, if not weeks. In this project we are working to both increase the longevity of short-term archival tag attachments, and to develop quantitative metrics and analysis tools to assess the impact of a tag on the animal. Here we will present: 1) the characterization of the mechanical properties of dolphin skin (*T. truncatus*) under vacuum loading; 2) the development of surface treatments that facilitate adhesive use as an alternative to suction cup attachments; 3) tag body designs that reduce net hydrodynamic loading; and 4) algorithm development and experimental design that enhance fine scale motion analysis for swimming animals.

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 30 SEP 2014		2. REPORT TYPE		3. DATES COVERED 00-00-2014 to 00-00-2014	
4. TITLE AND SUBTITLE Improving Attachments of Non-Invasive (Type III) Electronic Data Loggers to Cetaceans				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, Woods Hole, MA, 02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

APPROACH

Our approach is divided into four subtasks:

Task 1: Forces and failure modes in suction cup attachments. Define assays to investigate cup failure modes.

Task II: Assessing the impact of tags and surface attachments on cetaceans. Using Computational Fluid Dynamics we will assess the drag forces created by various suction cup and tag housing combinations.

Task III: Engineered suction cups and surface treatments for improved attachment. In the light of Tasks I and II we will engineer suction cups with longer duration using selected materials and molding techniques, cup surface treatments, and investigate the use of adhesives.

Task IV: On-animal performance of engineered attachments and tags. Using free swimming animals, first in captivity and then on stranded releases and animals tagged at sea, we will attach the engineered system with an instrumented cup to test cup behavior and longevity.

RESULTS

Task I: Cup Testing on Managed Animals at Dolphin Quest O'ahu

Objective: Measure the material properties of bottlenose dolphin skin under vacuum loading and identify the forces that result in cup failure using controlled loading. Individual cup failure forces were measured with custom instrumentation to determine specific modes of attachment failure.

Method: A custom set of electronics was used to simultaneously measure the applied load and internal pressure in the suction cups. The setup consisted of a load cell and five pressure sensors (four to measure internal cup pressure and one for atmospheric pressure), Figure 2. Sensor data are logged using an external computer housed in a portable waterproof container. Measurements of an individual cup and arrays of cups were made on cadavers, additionally individual cup failure forces were measured on live animals. Initial testing was conducted on a common dolphin (*D. delphis*) cadaver that had been frozen shortly after death, Further testing was conducted at Dolphin Quest O'ahu on live bottlenose dolphins (*T. Truncatus*).

Results: In addition to the cadaver work with tag models, the failure force of individual suction cups was examined with live animals at Dolphin Quest. Figure 2 shows representative data from the cup failure testing. The cups were loaded to represent drag loading on the cup (applied force parallel to the attachment surface) and lift loading (applied force perpendicular to the attachment surface). The results indicate that the failure force that results in sliding on the animal is much lower than the force that results in a detached cup.

Impact/Applications: The lift and drag forces generated by the tag must be resolved at the point of attachment if the tag is to remain on the animal. Cup detachment is likely to be a complex function of the loading and the substrate shape and properties, and so will not occur consistently at a predictable speed. Surface roughness was not measured at the attachment sites but is uniformly low on dolphins. In contrast to drag loading, lift loading is countered directly by an increase in attachment force at the suction cups. For a suction cup attachment, loads applied to the tag are translated into pressure loading

on the skin. Suction cup attachments do not penetrate the skin, but the stress put on the skin, even at forces well below the failure force, could create bruising.

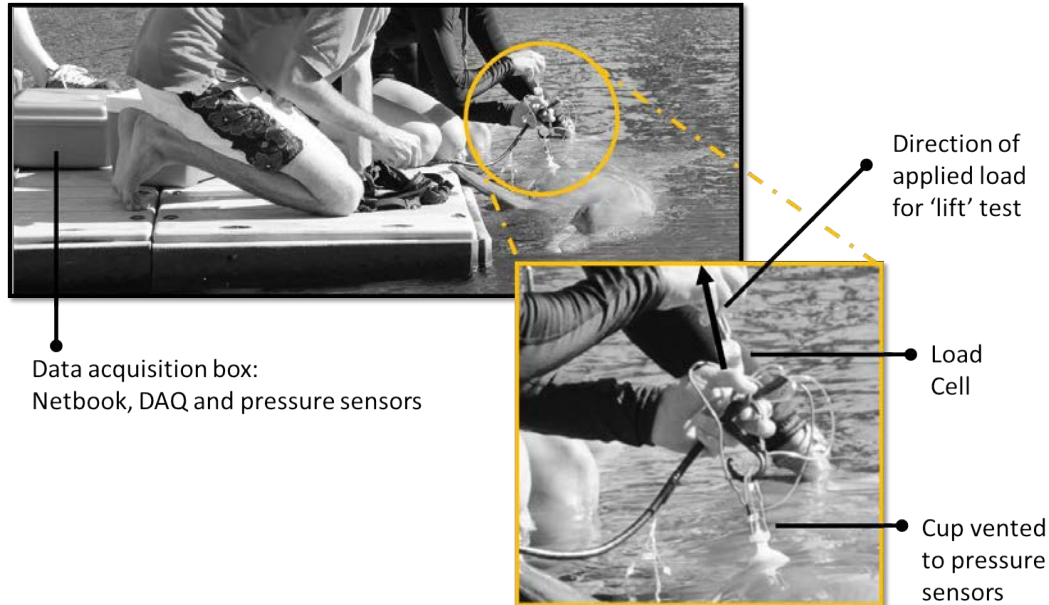


Figure 1 An example of the pull test electronics being used to measure failure loading of a single cup on a bottlenose dolphin at Dolphin Quest O'ahu.

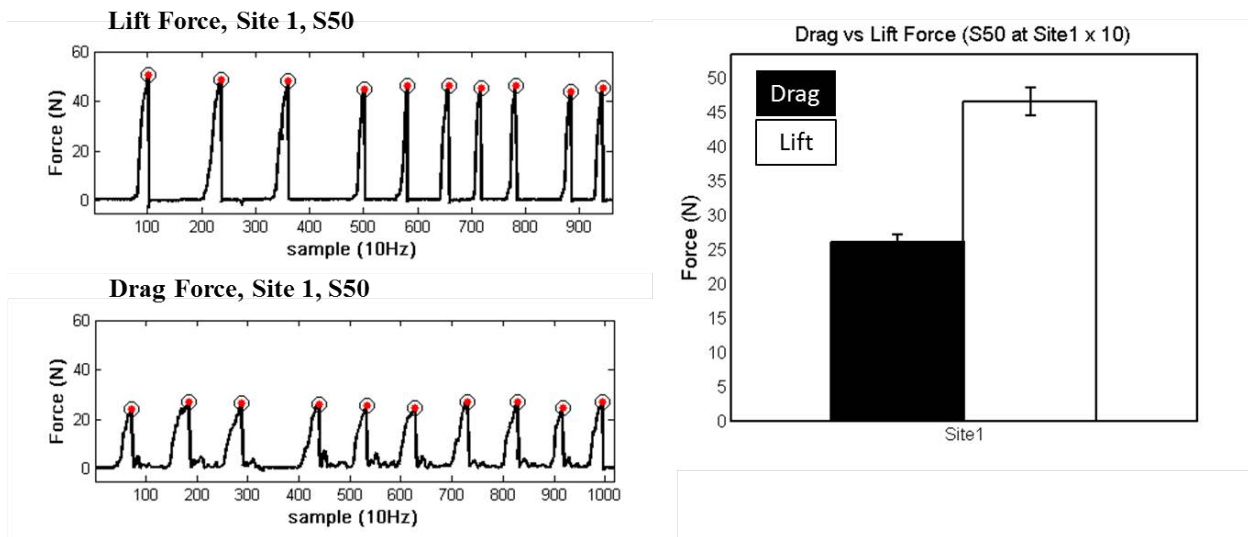


Figure 2 Representative data from pull testing of a single cup on a live animal at Dolphin Quest.

Task II: CFD modeling for improved tag design

Objective: During an on animal attachment the drag forces acting on the tag can remove the package or adversely affect the behavior or energetics of the animal. As such, tag packaging must be hydrodynamic to minimize the forces generated by fluid flow. Here we examine how flow control elements can be used to improve tag performance.

Method: In order to reduce lift and minimize total hydrodynamic loading we conducted a design study to compare the effectiveness of features that reduce flow speed differences around the housing (e.g., channels) and that redirect the flow to counter lift (e.g., fins). Hydrodynamic loading of four tag designs that use a combination of flow control elements, arrangements of a fin and channel together with a hydrodynamic body, were compared using computational fluid dynamics (CFD).

Results: The design with both fin and channel (Design A) performed best, eliminating all lift force and generating up to 80 N of downward force in simulated 10 m/s aligned flow, Figure 3. The channel alone (Design B) reduced drag on the package but did not reduce lift, while the wing only model (Design C) decreased drag and increased lift. The model with no flow control features (Design D) created drag and lift forces that were comparable to the channel only model (Design B).

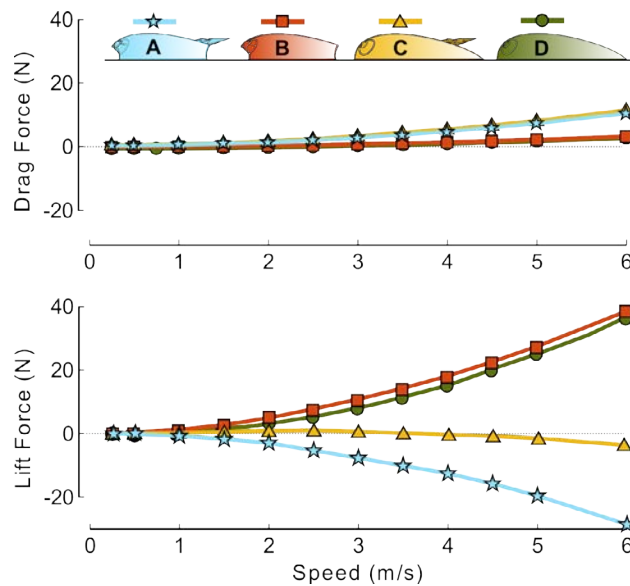


Figure 3 CFD simulation results for the four designs examined in the study: (A) wing and channel; (B) only channel; (C) only wing; (D) no wing or channel. The direction of the flow was aligned with the tags in all simulations

Impact/Applications: Flow control elements can be used to eliminate lift forces created by large flow speeds. The combined use of a streamlined housing, a channel, and a fin results in a large downward force on the tag with only a minimal increase in the drag on the package. This force acting to hold the tag to the attachment surface could be potentially beneficial for improved tag attachment longevity and will be investigated further.

Task III: Engineered suction cups and surface treatments for improved attachment

Objective: First, develop and then characterize micro textures and surface treatments that can be used to improve the adhesive bond between and engineered surfaces and cetecean skin. Next, test the strength of the adhesive bond and the impact of failure on cetacean skin first with cadavers and then with live animals.

Methods: A biocompatible cyanoacrylate (Vetbond) was used to glue a urethane base assemble to a cadaver. We glued assemblies with and without the texture and surface treatment to a common dolphin

cadaver and tested the bond to failure. The tested assembly consisted of a tag body modeled after design (from the above flow study) and a two part urethane base secured to the bottom of the tag body on either side of the channel. A line was secured to the front of the tag body and used to apply a shear force to the adhesive attachment. An inline load cell was used to measure the applied force up to failure.

Results: Results demonstrated that the texture and surface treatment uniformly distributed the glue over the attachment surface and significantly improved adhesion to the cadaver, Figure 4A. Further, the adhesive bond of the textured assembly resisted forces in excess of 70 N, more than twice the drag force predicted for this tag in 10 m/s flow, Figure 4B.

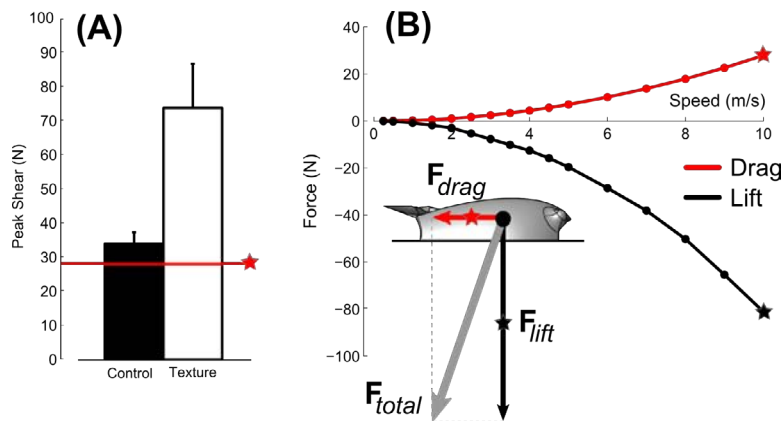


Figure 4 (A) The textured wings will resist the predicted drag forces in 10 m/s flow. **(B)** Simulation of the lift and drag forces that this tag body will experience in steady state inline flow. Negative lift generated by this tag design will help resist the peel moments that resulted in failure during the testing, and the predicted drag forces are lower than the glue failure force.

Impact/Applications: These preliminary results indicate the important role surface treatment and preparation play in a strong adhesive bond. Further, the strength of the bond that was achieved during the cadaver testing shows that glue has the potential to be an alternative to suction cups for tag attachment. Importantly, when the adhesive bond did fail, only the outermost layer of the skin was removed (approximately 5 μm thick), and the majority of the tag area failed at the glue-skin interface rather than within the skin.

Task IV: On-animal performance of engineered attachments and tags

Objective: Develop the tag technology and algorithms required to produce quantitative metrics for the assessment tag impact on animal health and well-being. Specifically, we are working to develop methods that will enable the accurate estimates of work and energy from on animal tag data.

Methods: We deployed a tag with a nine-degree-of-freedom inertial measurement unit (three axis accelerometers, magnetometers, and gyroscopes), that was encapsulated and secured to the animal with suction cups. During the deployments, the animals had periods of free swimming as well as structured enrichment activities where the dolphins were trained to follow a remote controlled (RC) boat.

Results: Representative data from an animal during RC boat following (Figure 5 left) and free swimming (Figure 5 right). The magnitude of the acceleration recorded by the tags is presented in the top two plots, and is three times higher during the enrichment task. Using gyroscope sensor integration and advanced sensor fusion algorithms we can also quantify fine scale gait data such as fluking rate, amplitude, and the resulting velocity of the animal during swimming. Separate gaits were observed during the trials. A cruising gait with regular fluking was used to follow the boat (bottom left), while a fluke and glide gait was used during the free swimming (bottom right). Importantly, the gait plots clearly illustrate differences between the less accurate accelerometer based estimate of body orientation (grey lines) and the more accurate estimate that uses information from all the inertial sensors (accelerometers, magnetometers, and gyroscopes). The improved estimate of the animal's orientation provided by the full set of inertial sensors is especially key for accurate estimates of inertial forces, velocity, and animal position.

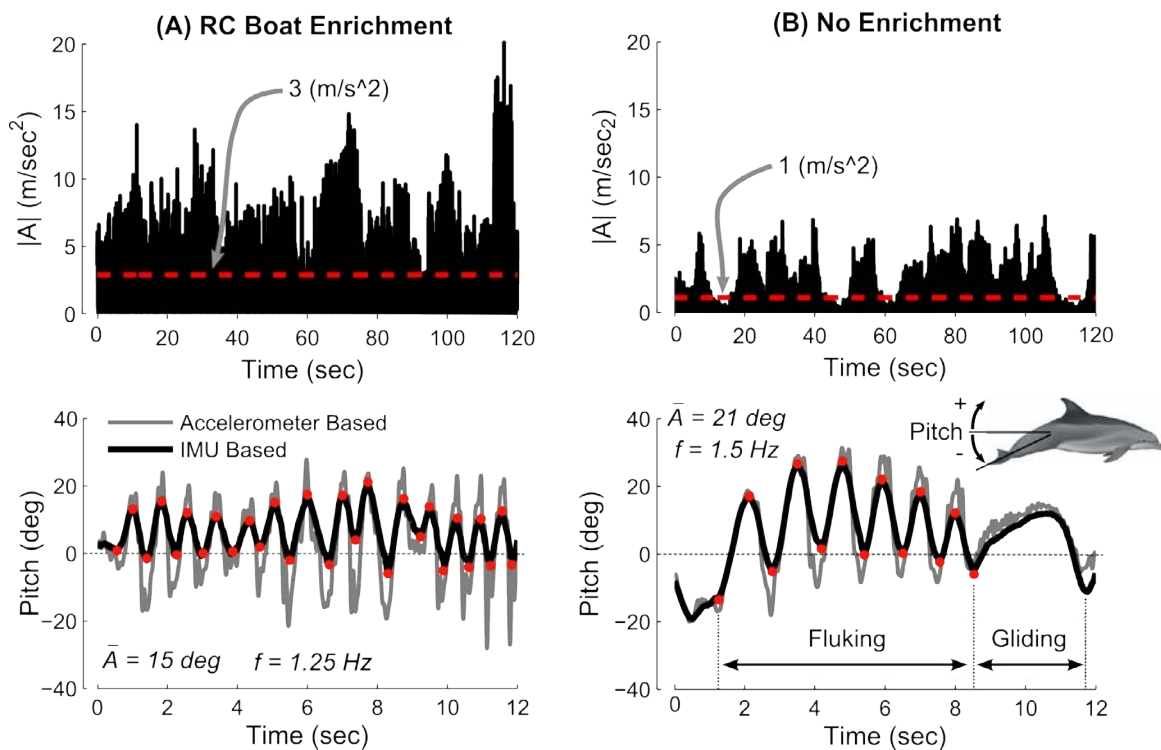


Figure 5 Data from an animal during RC boat following (left) and free swimming (right).

Impact/Applications: Typical data analysis among the animal bio-logging community uses only accelerometers and magnetometers to estimate an animal's orientation. Here we also use information from gyroscopes to provide a more accurate estimate of the animal's orientation and inertial accelerations, key components of fine scale motion analysis. Importantly, these are among the first results that present an analysis of a dolphin's swimming gait using a full set of inertial sensors. This ability to provide quantitative information, currently not available for any marine mammal, about animal health and activity has the potential to revolutionize how animals are cared for in these facilities.

PUBLICATIONS

Publications and Conference Proceedings for Year 4:

I. The following abstract was presented at the World Congress of Biomechanics (WBC) Boston, Massachusetts, July 2014.

In-vivo measurement of soft tissue with applications towards quantifying mechanical properties of marine mammal skin

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In-vivo measurement of the mechanical properties of skin, and underlying soft tissue, is of importance for applications ranging from teleoperated surgical systems to the design of lower-limb prosthetic socket interfaces. The work presented here was further motivated by the need to improve short-term suction cup attachments of bio-logging tags to smooth-skinned marine animals, where an understanding of the skin is paramount. Unlike rigid substrates, the viscoelastic properties of skin result in surface deformations into the cup under vacuum loading, reducing cup attachment force, and potentially creating localized barotrauma. The amount of creep into the cup will depend on vacuum force, cup stiffness, and the material properties of the skin at the attachment site. This work presents the design and experimental demonstration of a custom measurement tool, termed the Static Suction Cup (SSCup), to facilitate the investigation of vacuum loading on skin. In this work, we hypothesize that the bulk properties of the skin will vary at different locations, and ingress of tissue into the cup will reduce the attachment force of the suction cup. The SSCup was used to investigate the mechanical properties of skin under vacuum loading on eleven live bottlenose dolphins (*Tursiops truncatus*). Three vacuum profiles were used to load the skin: **A)** step vacuum loading to a 0.3 bar differential; **B)** repetitive pressure loading at low (0.5-0.1 bar), medium (0.5-2 bar), and high (0.5 to 3 bar) ranges; and **(C)** static loading (0.3 bar). Three sites with varying anatomical substructure were examined: **(1)** the back of the animal, a location with significant subcutaneous fat; **(2)** above the pectoral flipper, which overlies muscle on the blade of the scapula; and **(3)** near the dorsal fin insertion, which has increased blubber fiber content as part of the dorsal fin saddle. During testing, nonlinear stiffness was observed at all three sites, but Site **(3)** was stiffest and showed low hysteresis, while Sites **(1)** and **(2)** both showed distinctly lower stiffness and higher hysteresis, Figure 1. These results demonstrate that suction cups may preform differently depending on attachment location, and support our hypothesis that bulk skin properties vary by locations.

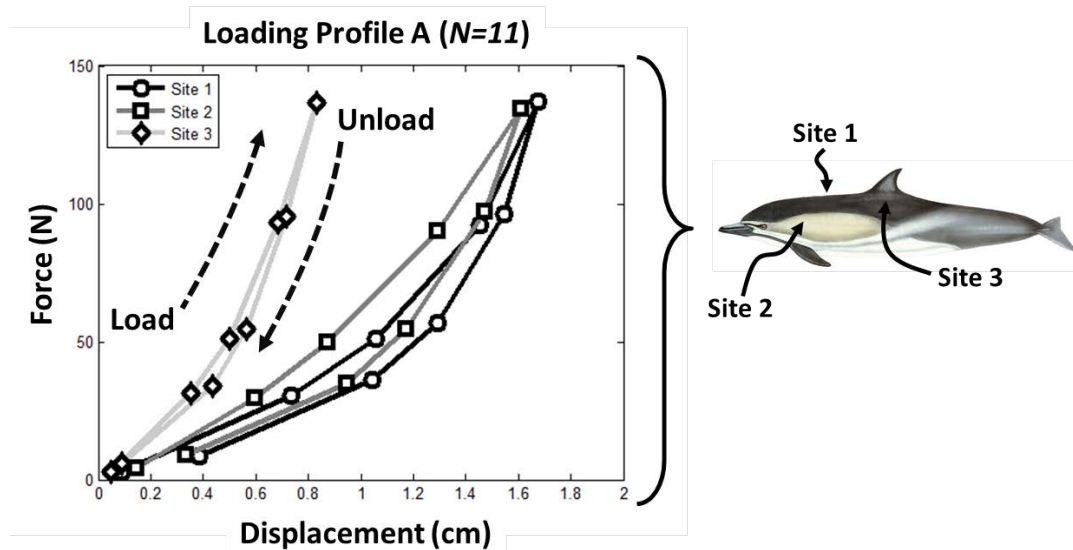


Figure 1 Force vs displacement curves for dolphin skin under step vacuum loading. The three sites were selected because of the varying anatomical substructure at these locations.

II. The following abstracts were accepted for the 5th Bio-logging Science Symposium in Strasbourg, France, Sept 2014.

A) Reducing impact: design features to minimize hydrodynamic forces for suction cup tags on swimming animals

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Bio-logging tags are an important tool for the study of marine mammals, but superficial tags inevitably increase hydrodynamic loading. For tags on fast-swimming animals substantial forces can be generated potentially affecting behavior and energetics, or promoting early tag removal. Streamlined forms have been used to reduce loading, but these designs can accelerate flow over the top of the tag. This asymmetric flow results in large lift forces (normal to the animal) that become the dominant force component at high speeds. In order to reduce lift and minimize total hydrodynamic loading this work presents a comparison of design features that reduce flow speed differences above and below the

housing (*e.g.*, channels) and that redirect the flow to counter lift (*e.g.*, fins). Hydrodynamic loading of four tag designs that use a combination of flow control elements, arrangements of a fin and channel together with a hydrodynamic body, were compared using computational fluid dynamics (CFD). The design with both fin and channel performed best, eliminating all lift force and generating up to 80 N of downward force in simulated 10 m/s aligned flow.

B) The next generation of multi-sensor acoustic tags: sensors, applications and attachments

Nowacek, D.P., Bowers, M., Cannon, A., Hindell, M., Howle, L.E., Murray, M.M., Rittschof, D., Shorter, K.A., and Moore, M.

From Kooyman's 1963 wind-up kitchen timer TDR, multi-sensor tags have evolved significantly over the last twenty years. These advancements, including high fidelity acoustics, have been driven by improved sensing and electronics technology, and resulted in highly integrated mechatronics systems for the study of free ranging animals. In the next decade, these tags will continue to improve and promising work has begun in three key areas: i) new sensors; ii) expanding uses of existing sensors; and iii) increasing attachment duration and reliability. The addition of rapid acquisition GPS and the inclusion of gyroscopes, to separate the dynamic acceleration of the animal from gravitational acceleration, are underway but not widely available to the community. Existing sensors could be used for more and different applications, *e.g.*, measuring ambient ocean noise. Tags attached to pinnipeds in the Southern Ocean, for example, could provide noise measurements from remote areas. Finally, attachment duration has been limiting for cetaceans, because the suction cups typically used do not reliably stay attached for more than a day. We will present data on engineering efforts to improve attachments: i) improved tag hydrodynamics; ii) incorporating bio-compatible glues; and iii) micro structuring tag components to utilize hydrostatic forces and enhance adhesion.

C) Acoustic parameters as indicators of metabolic rate in *Tursiops truncatus*

van der Hoop, Julie M.; Fahlman, Andreas; Jensen, Frants H.; Johnson, Mark; Brodsky, Micah; Hurst, Thomas; Rocho-Levine, Julie; Shorter, K. Alex; Moore, Michael J.

Respiratory sounds in humans offer a significant amount of information on lung pathology and physiology. Recording parameters from biologging devices can serve as proxies for variables that cannot be directly measured during deployments on free-ranging animals. Here we propose to use acoustic parameters of animal exhalations (peak-to-peak sound pressure level [dB re 1 μ Pa], 95% energy duration [s], and energy flux density [Pa² s]) as indicators of breath-by-breath respiratory measures (expiratory flow rate [L s⁻¹], tidal volume [L], and volume of expired O₂ [L]). To investigate these relationships we analyzed simultaneous respiratory and acoustic measurements from trained bottlenose dolphins before and after 10-minute swimming exercises. Breath-by-breath measurements of expired O₂ and CO₂ and respiratory flow rates were made via a pneumotachometer, and the sound of the exhalation was recorded by an acoustic tag (DTAG3) placed near the animal's blowhole with suction cups. Preliminary results from multiple linear regressions suggest energy flux density may be a reliable indicator of tidal volume ($R^2 = 0.81$). However, additional analyses are required to further establish this relationship. For example, sound deformation in the respirometry device and potential masking from flow or wave noise must be understood to enable metabolic rate estimates from free-ranging marine mammals.

IV. The following manuscript is currently under review in the Journal of Experimental Biology

Bottlenose dolphins modify behavior to reduce metabolic effect of tag attachment

van der Hoop, Julie M; Fahlman, Andreas; Hurst, Thomas; Rocho-Levine, Julie; Shorter, K. Alex; Victor Petrov; Moore, Michael J

Abstract

Attaching bio-telemetry or -logging devices ('tags') to marine animals for research and monitoring adds drag to streamlined bodies, affecting posture, swimming modes and energy balance. These costs have never been measured in free-swimming cetaceans. To examine the effect of drag from a tag on metabolic rate, cost of transport, and swimming behavior, four captive male dolphins (*Tursiops truncatus*) were trained to swim a set course, either non-instrumented ($n = 7$) or instrumented with a tag (DTAG2; $n = 12$), and surface exclusively in a flow-through respirometer where oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$; $\text{mL kg}^{-1} \text{min}^{-1}$) rates were measured and respiratory exchange ratio ($\dot{V}O_2/\dot{V}CO_2$) was calculated. Tags did not significantly affect individual mass-specific oxygen consumption, Physical Activity Ratios (exercise $\dot{V}O_2$ /resting $\dot{V}O_2$), total or net cost of transport (COT, $\text{J m}^{-1} \text{kg}^{-1}$) or locomotor costs during swimming or two-minute recovery phases. However, individuals swam significantly slower when tagged (by $\sim 11\%$; $\text{mean} \pm \text{s.d. } 3.31 \pm 0.35 \text{ m s}^{-1}$) compared to when non-instrumented ($3.73 \pm 0.41 \text{ m s}^{-1}$). A combined theoretical and Computational Fluid Dynamics (CFD) model estimating drag forces and power exertion during swimming suggests drag loading and energy consumption are reduced at lower swimming speeds. Bottlenose dolphins in the specific swimming task in this experiment slowed to the point where the tag yielded no increases in drag or power, while showing no difference in metabolic parameters when instrumented with a DTAG2. These results, and our observations, suggest that animals modify their behavior to maintain metabolic output and energy expenditure when faced with tag-induced drag.